Neoalpine tectonics of the Danube Basin (NW Pannonian Basin, Hungary)

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ABSTRACT

The structure of the pre-Tertiary substratum of the NW Pannonian Basin is traditionally interpreted in terms of subvertical Tertiary strike-slip faults controlling the subsidence of major pull-apart basins. However, based on a recent reevaluation of reflection-seismic data the middle Miocene structure of the basin is dominated by a number of low-angle normal faults.

The gently dipping basement of the European foreland can be traced some 200 km to the SE beneath the extensionally collapsed transition zone between the Eastern Alps and the Carpathians. This suggests a large-scale allochthoneity of the Alpine edifice underneath the NW Pannonian Basin.

The compressional pre-conditioning of the substratum of the Neogene NW Pannonian Basin was always assumed to be a key factor in the formation of extensional structures by reactivation of pre-existing weakness zones. Based on reflection-seismic data, such an interaction between Cretaceous compressional décollement levels and Miocene low-angle normal fault planes indeed occurred, although in more complex manner than previously assumed.

INTRODUCTION

This paper discusses the Neo-Alpine (sensu Trümpy, 1980) evolution of the area which straddles the junction between the Eastern Alps and the Western Carpathians and is occupied by the NW Pannonian Basin, more specifically by the Hungarian part of the Danube Basin. The following Neo-Alpine structural stages are recognized:

(1) Early Miocene "escape" tectonics which follow on the heel of the Paleogene Mesoalpine compressional phase,
(2) Middle Miocene syn-rift tectonics,
(3) Late Miocene-Pliocene post-rift tectonics and
(4) Quaternary-Recent neotectonics.

Tari, G., 1996. — Neoalpine tectonics of the Danube Basin (NW Pannonian Basin, Hungary). *In*: Ziegler, P. A. & Horváth, F. (eds), Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands. *Mém. Mus. natn. Hist. nat.*, **170**: 439-454 + Enclosures 1-3. Paris ISBN: 2-85653-507-0.

This article includes 3 enclosures on 2 folded sheets.

This papers focuses on problems related to the Mid-Miocene syn-rift tectonics which underlay the formation of the Danube and related basins (Fig. 1).

The middle Miocene Danube Basin has been interpreted by many authors (e.g. Bergerat, 1989; Vass et al., 1990) as a large pull-apart basin. In this paper I document the presence of a system of major low-angle normal faults in this basin which are evident on reflection-seismic data, calibrated by wells. The presence of these detachment faults and the lack of major throughgoing middle Miocene strike-slip structures contradicts the traditional pull-apart basin interpretation. Note that in this paper the terms low-angle and detachment fault are used interchangeably. The new observations and interpretations are summarized in a regional structural transect across the NW Pannonian Basin, more specifically, across the Danube Basin.

The Neoalpine Danube Basin, which forms part of the larger Pannonian basin complex is superimposed on an earlier Cretaceous and Paleogene compressional realm, as inferred from the Alpine structure of the surrounding thrust-fold belts, such as the Alps, Carpathians and Dinarides (Fig. 1). Based on well and reflection-seismic data, these structures can be traced with considerable confidence at depth through the Danube Basin (Figs. 2 to 4). Moreover, these data show, that the compressionally pre-conditioned "memory" of the substratum of the Neogene Danube Basin played a significant role in localizing Miocene extensional faults, partly involving the tensional reactivation of pre-existing compressional decollement levels (e.g. Grow et al., 1989; Tari et al., 1992). The seismic line drawings given in this paper (see also Tari and Horváth, 1995; Tari, 1995a) show that reactivation of abandoned Eoalpine thrust fault planes occurred frequently, however, in a more complex manner than anticipated by many authors.

GENERAL NEOALPINE TECTONO-STRATIGRAPHY OF THE NW PANNONIAN BASIN

The locally very thick Neogene sedimentary fill of the NW Pannonian Basin, which exceeds in the centre of the Danube Basin 8 km, can be subdivided into two major units (for an overview see Royden and Horváth, 1988). The upper unit is late Miocene to Pliocene in age (Sarmatian/Pannonian; 13.8-0 Ma) and forms the post-rift sedimentary succession which accumulated in response to regional thermal subsidence of the area. The thickness variation and spatial distribution of the underlying middle Miocene (Karpatian/Badenian; 17.5-13.8 Ma) succession is largely controlled by syn-rift structural features. Deposition took place in fault-bounded half-grabens. Some of the deeper subbasins of the Pannonian Basin were clearly formed by extensional detachment faulting (Tari et al., 1992).

Note that I placed the syn-rift/post-rift boundary stratigraphically earlier than Royden et al. (1983). Commonly this boundary is placed at the Pannonian/Sarmatian boundary (i.e. ~10.5 Ma); however, based on a review of the available well and seismic data this boundary must be placed between the upper and middle Badenian, some 3.3 Ma earlier (for a detailed discussion, see Tari and Horváth, 1995).

STRUCTURE OF THE DANUBE BASIN BASED ON REFLECTION SEISMIC DATA

The following discussion on the structure and evolution of the Danube Basin is based on a systematic structural and seismostratigraphic interpretation of a reflection-seismic grid, including some 200 lines covering the Hungarian part of the NW Pannonian Basin (Tari, 1994).

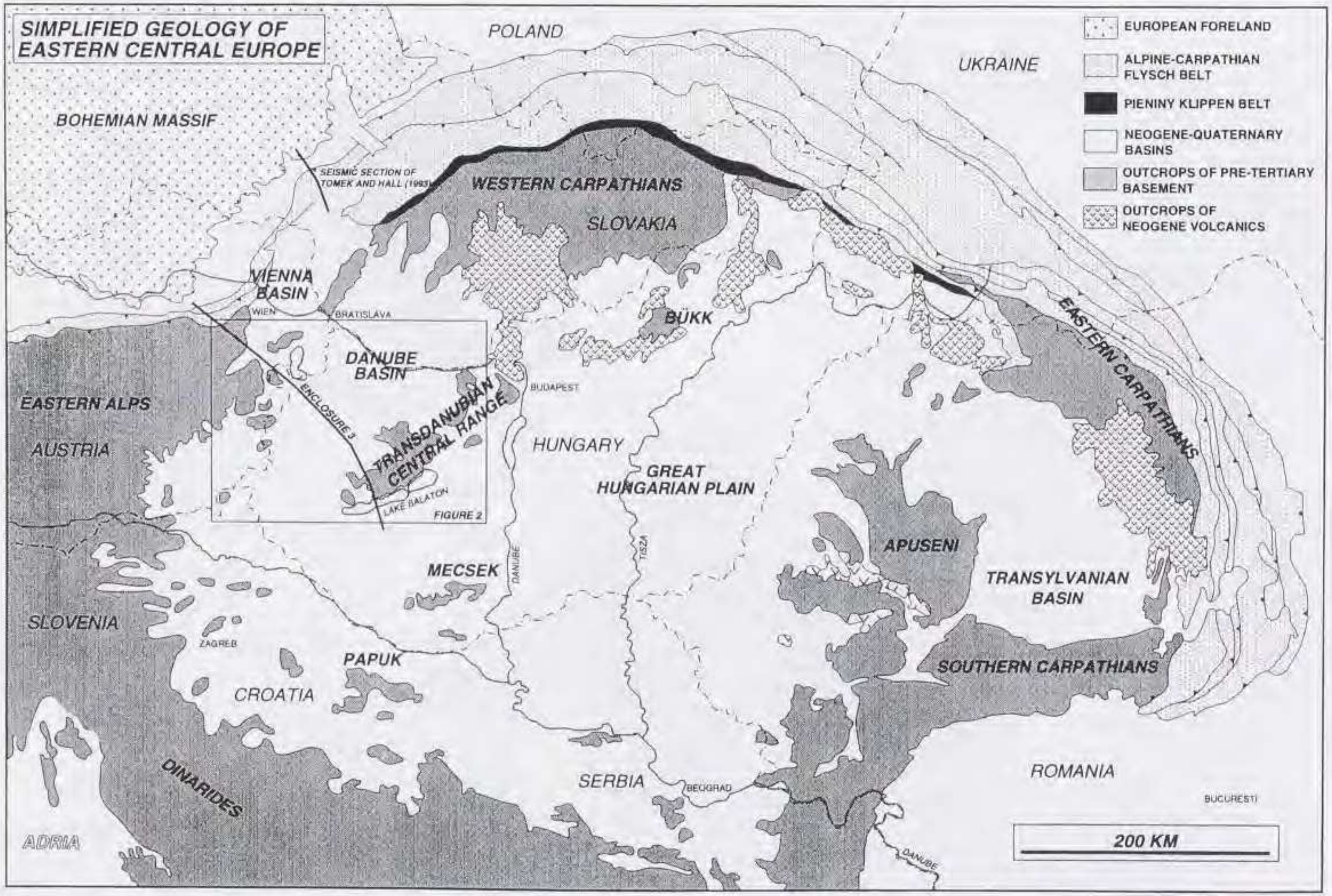

FIG. 1. Simplified geologic map of the Carpathian/Pannonian system showing the location of this study.

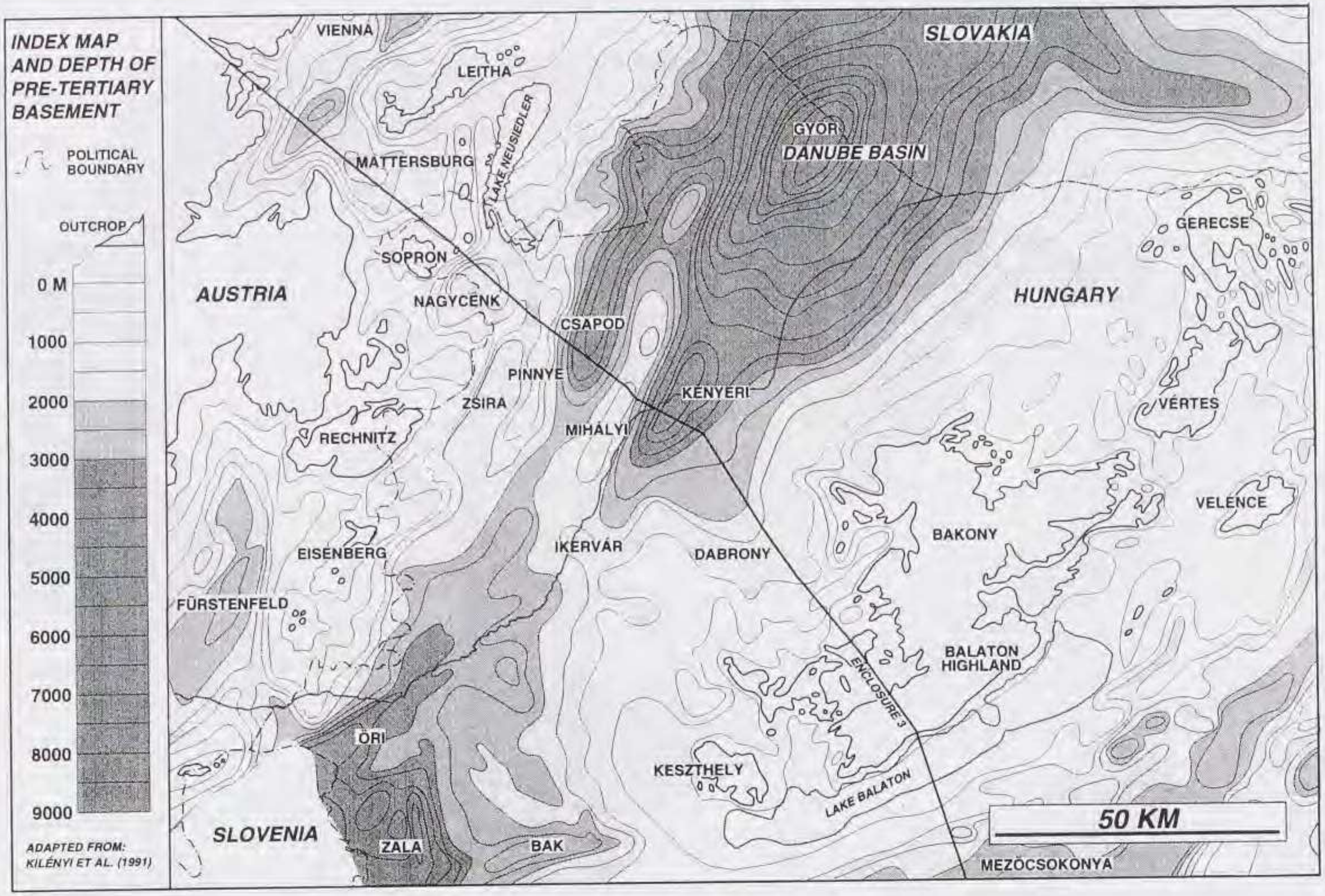

FIG. 2. Index map and depth of pre-Tertiary basement in the NW Pannonian Basin. For location see Fig. 1.

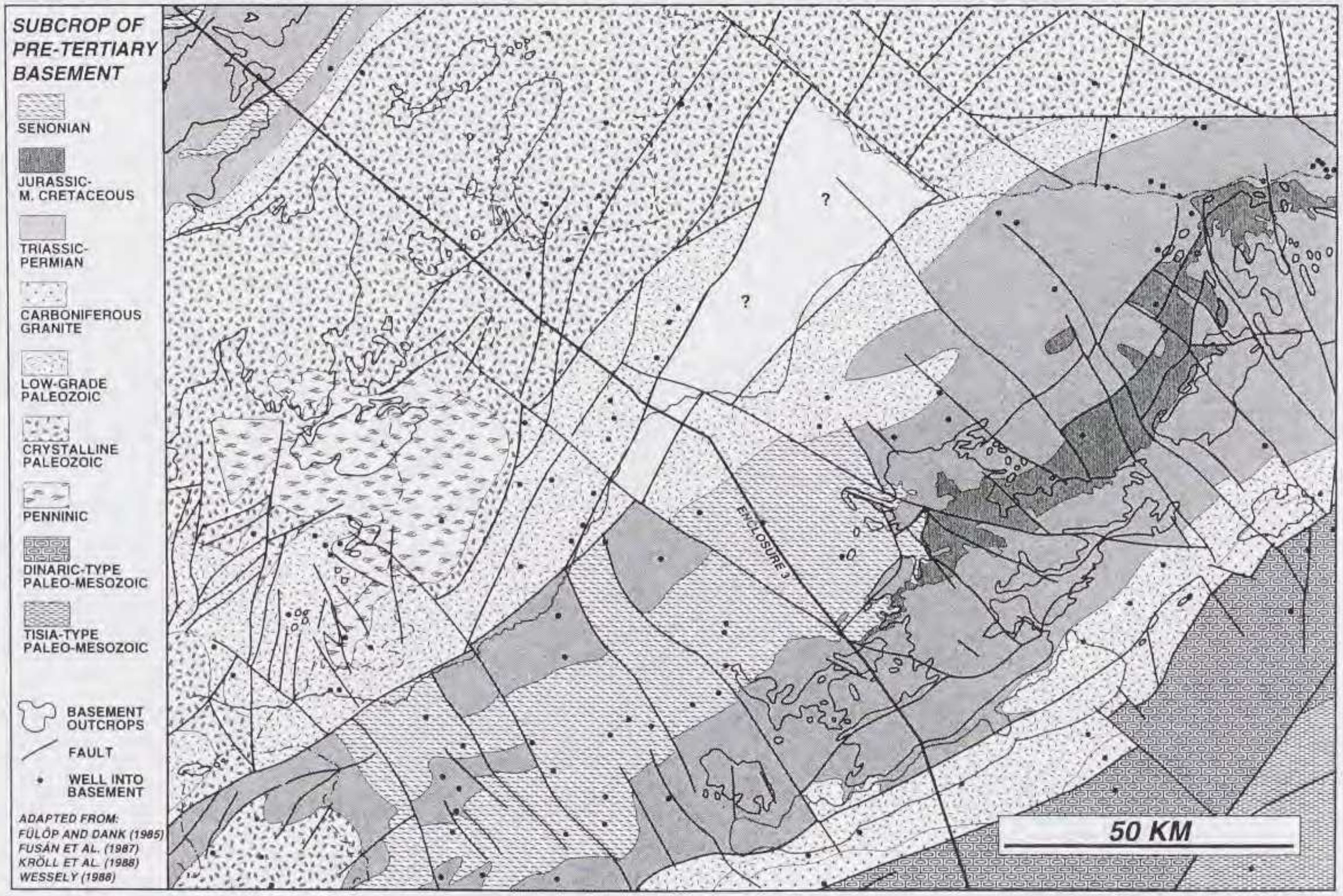

FIG. 3. Subcrop of pre-Tertiary basement in the NW Pannonian Basin. For location see Fig. 1.

Seismic Data Set

From this extensive data set five characteristic seismic profiles were selected; these are given in Enclosures 1 and 2. Three additional profiles from the same area were presented by Tari and Horváth (1995). Whereas the deep reflection profile of Posgay et al. (1986) is shown in Encl. 1 with and without interpretation, four industry-type reflection-seismic lines are reproduced as line drawings on Encl. 2. All the sections are migrated and the industry profiles are displayed at a 1:1 scale for a velocity of 5,000 m/s (16,400 ft/s); datum is 100 m (328 ft) above sea level.

Alpine Stratigraphy in Terms of Seismic Signatures

Fig. 5 gives a simplified summary of the stratigraphy of the Hungarian part of the NW Pannonian Basin; it is based on a detailed Phanerozoic lithostratigraphy described by Tari (1995b). While the thickness data are well known for the upper 10 km of this composite section, thickness relations are poorly constrained for the Palaeozoic of the Austroalpine units and for the Mesozoic of the Penninic unit. Interval velocities of the major units were compiled based on velocity surveys in selected wells and reported interval velocities in several seismic surveys. Fig. 5 also shows the interval velocities which were adopted for the depth-conversion of selected seismic sections. Moreover, its righthand column identifies the seismic mapping horizons as shown in Enclosures 1 and 2.

Characteristic Reflection Seismic Examples

Enclosure 1 shows the MK-1 deep reflection profile (for location see Fig. 4) of Posgay et al. (1986) as well as its line drawing interpretation by Tari (1994).

At the NW end of this line, Palaeozoic crystalline rock, attributed to the Lower Austroalpine nappes, crop out in the area of the Sopron Mtns. (Figs. 2 and 3); well data near the trace of this line indicate that Palaeozoic basement holds up also the Pinnye High (Kőrössy, 1987), seen at line km 18. This high is flanked by two Neogene half-grabens, the Nagycenk Basin to the NW and the Csapod Basin to the SE (Ádám et al., 1984). The Mihályi High, evident near line km 40, is upheld by low-grade metamorphic Palaeozoic rocks (Balázs, 1971, 1975).

Both the Pinnye and Mihályi highs are bounded on their SE flank by major low-angle normal faults on their SE side (see below the industry seismic profiles). The fault which bounds the Mihályi High has been referred to by several authors as the Rába fault (for a detailed discussion see Szafián and Tari, 1995). To the S of this fault, the basement is covered by a Late Cretaceous sedimentary succession. At line km 50 the middle Miocene syn-rift sequence shows a clear thickening in the Kenyeri subbasin of the Danube Basin. Further to the SE, pronounced reflector packages within the pre-Senonian basement suggest the presence of a number of NW vergent thrust faults (Tari, 1995a).

The four industry seismic lines, for which line drawings are given in Encl. 2 come from the northwestern part of the Hungarian Danube Basin (Fig. 4). In this area, the Neogene basin fill displays a general monoclinal dip to the E. While the post-rift Pannonian succession covers all the pre-Tertiary basement structures, the syn-rift middle Miocene (Karpatian-Badenian) can be found only in local subbasins, delimited by faulted basement highs. The two prominent Bük-Pinnye and Mihályi-Mosonszentjános basement highs strike to the NE-N and delimit the Csapod subbasin (Fig. 2).

Starting from the SW, the consecutive dip-oriented (i.e. NW-SE) seismic sections C1, C3 and C5 reveal the gradual deepening and widening of the Csapod subbasin that is related to an increase in offset along a major detachment fault on its northwestern flank. This clearly low-angle fault flattens at depth and therefore can be regarded as a listric normal fault sensu Bally et al. (1981). This fault corresponds to the Alpokalja or Répce Line of Fülöp (1989, 1990), separating low-grade metamorphosed Palaeozoic rocks from crystalline rocks. The seismic data clearly show that this fault is not a strike-slip fault (cf. criteria given by Harding, 1990), as previously suggested by a number of

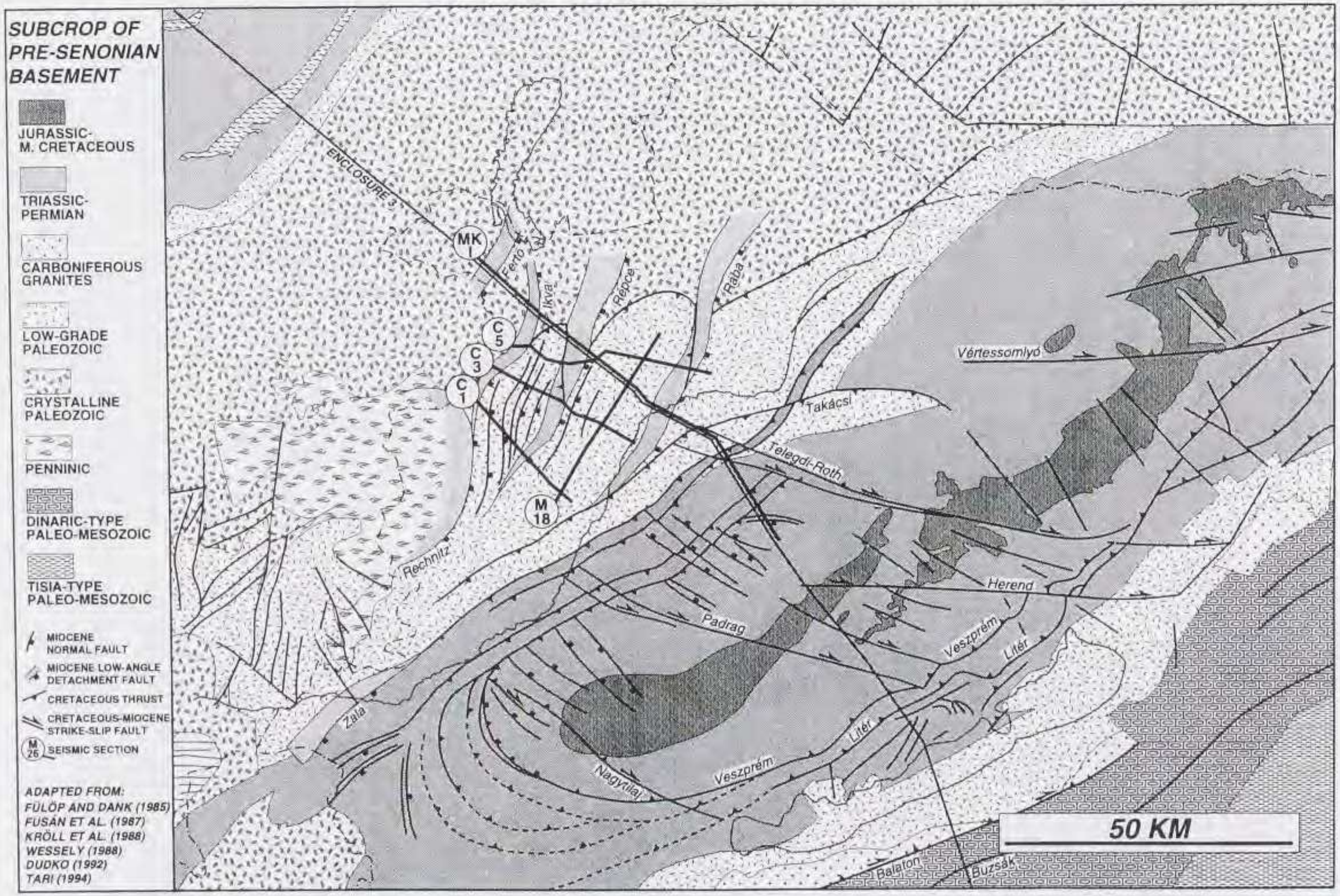

FIG. 4. Subcrop of pre-Senonian basement and Alpine structural elements revealed by reflection-seismic data in the Hungarian part of the NW Pannonian Basin (Tari, 1994), compare Fig. 3. For location see Fig. 1.

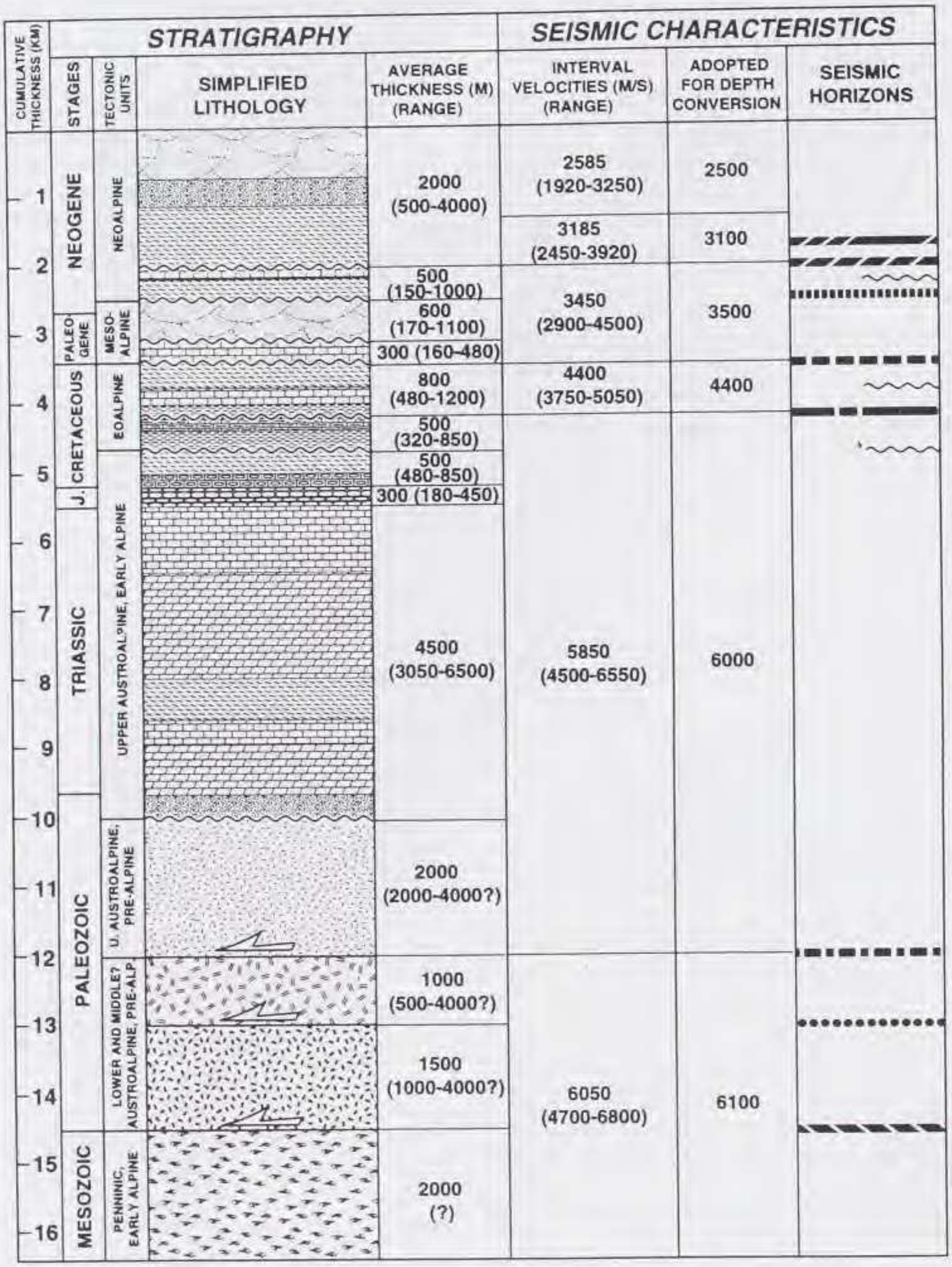

FIG. 5. Lithology and seismic characteristics in the NW Pannonian Basin (Tari, 1994).

REGIONAL STRUCTURE TRANSECT BASED ON DEPTH-CONVERTED REFLECTION SEISMIC SECTIONS

The location of the regional transect given in Encl. 3 is shown on Figs. 1 to 4. This section starts in the N in the European foreland, crosses the Eastern Alps, the Vienna and Danube basins, and terminates in the S at Lake Balaton, at the Mid-Hungarian shear zone.

The northern, Austrian part of this transect is based on a section published by Wessely (1987). In the Eastern Alps three tectonostratigraphic levels are recognized (Wessely, 1988). The lowermost level corresponds to the crystalline basement of the European foreland and its autochthonous Mesozoic cover which dips gently to the S. Beneath the Vienna Basin, the autochthonous Mesozoic cover is preserved. This cover is, however, missing under those parts of the Eastern Alps which are located in the projection of the Bohemian Massif; over this basement spur, which was intercepted by the well Berndorf 1, Mesozoic strata were eroded in conjunction with latest Cretaceous and Palaeocene compressional foreland deformations (Wessely, 1987). To the NW of this well, the European foreland crust is covered by deeply eroded autochthonous Mesozoic series, thin Late Eocene sands and carbonates, Oligocene-early Miocene flysch and middle Miocene molasse (Zimmer and Wessely, this volume) .

The next level is represented by the allochthonous Alpine nappes, which outcrop to the W of Vienna (Fig. 1). The tectonically highest unit corresponds to the Upper Austroalpine nappes; in the Northern Calcareous Alps these can be subdivided from top to bottom into the Upper Limestone Alps and Graywacke zone (Juvavicum), Ötscher nappes (Tirolicum, or Göller nappe system) and the Frankenfels-Lunz nappe system (Bajuvaricum, Hamilton et al., 1990). All these nappes are "cover nappes" (Tollmann, 1989), in so far as they were detached from their basement. These nappes exclusively consist of unmetamorphosed Mesozoic sediments, except for the uppermost Juvavic nappe which has a low-grade metamorphosed Palaeozoic substratum (Graywacke zone). These units are underlain by the Middle and Lower Austroalpine thrust sheets which also outcrop along strike. The presence of a Penninic unit at depth is problematic in the area of the Vienna Basin due to lack of well control (Wessely, 1988; Zimmer and Wessely, this volume).

The uppermost level is represented by the Neogene succession of the Vienna Basin. The structure section crosses the southwestern corner of this basin (Fig. 2), where normal faults bound the 2-3 km deep Neogene basin. These normal faults are shown to sole out and merge with the base of the underlying Alpine nappe complex (Encl. 3). Note that this is the only modification I made to the original sections of Wessely (1988), who thought that the normal faults also affected the autochthonous European foreland crust. These normal faults were thought by many authors to accommodate sinistral strike-slip movements required for the opening of the Vienna pull-apart basin (Royden et al., 1982; Fodor, 1991, 1995; Fodor et al., 1990). The inferred left-lateral offsets along these major faults, however, could not be documented (Wessely, 1988).

The Vienna Basin is separated from the Danube Basin, which underlays the Little Hungarian Plain, by a composite basement high which trends perpendicular to this transect. This high consists of the Leitha and Sopron Palaeozoic basement blocks (Fig. 2) which are attributed to the Lower Austroalpine unit. These blocks are bounded to the southeast by major normal faults and are separated by the small Mattersburg Neogene basin.

The section crosses the Austrian/Hungarian border just to the N of the Sopron Mts. and from there follows the trace of the deep reflection-seismic section MK-1 given in Encl. 1 (Ádám et al., 1984; Posgay et al., 1986). Further to the S, the section follows the continuation of the MK-1 line through the Bakony Mts., which was processed only to 4 s TWT time (Ádám et al., 1985). This part of the section, however, is constrained by surface geology (e.g. Császár et al., 1978).

In the northwestern part of the Danube Basin the pre-Tertiary basement exhibits a characteristic basin-and-range morphology. Individual subbasins (Mattersburg, Nagycenk, Csapod, Kenyeri) are separated by basement highs (Leitha, Sopron, Pinnye, Mihályi). All of these subbasins are controlled by major SE-dipping middle Miocene normal faults. The crustal section clearly shows that at authors. In the following this low-angle normal fault is referred to as the **Répce fault** (Tari, 1994).

The Répce fault plane itself can be traced between the terminations of more or less coherent SE-dipping basement reflectors of the Pinnye high and the overlying chaotic seismic facies which corresponds to coarse-grained clastics shown stippled on profiles C3 and C5. This facies unit represents alluvial talus which was deposited synchronously with the initial activity of the Répce fault. This facies unit was penetrated by the nearby Csapod-1 well which encountered an about 500 m thick Karpatian succession of conglomerates and breccias (Körössy, 1987).

The Badenian syn-rift fill of the Csapod subbasin is just slightly asymmetric and documents only little or negligible fault growth. This indicates that much of the normal faulting had occurred right at the beginning of rifting, i.e. during the Karpatian. Strikingly similar seismic examples of analogue basins were published from the Basin and Range province by Effimov and Pinezich (1981) and from the Newark Basin by Costain and Coruh (1989).

Interestingly enough, coherent basement reflector packages below the Mihályi High described a roll-over anticline (section C5) which apparently is associated with the large normal offset on the Répce detachment fault. The normal offset on this fault can be estimated by restoring displaced prominent basement reflectors in the Bük-Pinnye and Mihályi-Mosonszentjános highs. Such reconstructions suggests that the magnitude of offset along the Répce fault varies along strike between 4-10 km (horizontal component), with error bars being on the order of 0.5 km.

Note that, within the basement, the Répce detachment fault shows up as prominent fault-plane reflectors (section C1). Comparable fault plane reflectors, originated from similar detachment fault planes, were reported from Utah (e.g. von Tish et al., 1985) and Arizona (e.g. Frost and Okaya, 1986).

Since many intra-basement reflecting horizons could be correlated with considerable confidence in this area, I mapped certain Eoalpine basement units based on their seismic character (Tari, 1994). The best geometric constraint is provided by the Penninic succession which has a very distinct, highly reflective seismic expression and a well-defined top (section C1).

Since the Upper Austroalpine unit is lithologically markedly different from the Middle Austroalpine (very low-grade to low-grade versus medium-grade metamorphics) their contact is interpreted to correspond to a pronounced change in reflectivity (section C1). The Upper Austroalpine unit is characterized by short, but strong reflectors in contrast to the underlying Middle Austroalpine which has a mostly transparent character.

In the S, the Upper Austroalpine unit can be found right on top and in fault contact with the Penninic(section C1). This relationship was indeed observed along strike in outcrop at the Eisenberg Mountains (Figs. 2 and 4) where the Upper Austroalpine Hannersdorf series have a poorly understood tectonic contact with the Penninic succession (e.g. Pahr, 1980; Schmidt et al., 1984; Tollmann, 1989).

On sections C1 and C3 another detachment fault can be interpreted to the NW of the Bük-Pinnye high which controlled subsidence of a smaller syn-rift graben. Tari (1994) referred to this detachment fault as the **Ikva fault** and to the associated basin as the Zsíra subbasin (Fig. 2). In the S the Ikva fault is detached on top of the Penninic unit. Farther to the NE, however, the fault shows gradually decreasing normal offset and flattens out close to base of the inferred Middle Austroalpine unit (section C5).

Whereas in the S (section C1) the Répce fault seems to flatten close to or into the boundary between the Upper/Middle Austroalpine units (see strike section M18), it apparently ramps down to deeper structural levels along strike, i.e. to the NE. As can be shown on a number of strike sections, the Répce fault plane describes a synform, the axis of which plunges to the SE. Note that this pronounced synclinal feature is remarkably displayed on section M18. Looking at several dip lines, the Répce fault has a pronounced "spoon" shape in the basement with maximum displacement along the long axis of the spoon. Interestingly enough, the Répce fault plane climbs up in terms of physical depth farther to the NE, but it ramps down in a tectonostratigraphic sense into the Lower Austroalpine unit (section M18).

least the Fertö and Répce faults maintain their low-angle dip (~30-40°) to mid-crustal depth. Moreover, the Fertö fault (also called Balf fault by Fodor, 1991) appears to merge at depth into a prominent surface which I interpret as the base of the Austroalpine nappe complex. The mid-crustal geometry of the Rába fault is not clear because the data deteriorate in the southeastern part of the crustal profile.

The average dip (~5°) of the European foreland in the northwestern part of the transect is well constrained by the wells Raipoltenbach-1 and Berndorf-1. Extrapolating this dip to the SE, the top of the European foreland can be tied into the northwestern end of the crustal profile MK-1 given in Encl. 1. A prominent reflection doublet at 4.2 s TWT time (~11 km depth) is interpreted as originating from the boundary between the autochthonous European foreland crust and the overriding Alpine nappes. This reflection event can be correlated further to the SE with a slightly steeper dip (~10-15°), to about 20 km depth, beneath the Mihályi high. Beyond this point, poor seismic data quality does not permit to follow this surface farther to the SE (Encl. 1). Subhorizontal to slightly SE-dipping strong reflector packages below this interface are thought to emanate from crystalline rocks of the European foreland crust. Beneath the Pinnye high, at about 6 s TWT time (~14-18 km), some strong NW-dipping reflectors are tentatively interpreted as being related to a 10-15 km wide Mesozoic (Jurassic?) half-graben located in the distal parts of the European passive margin. The boundary fault of this half-graben dips toward the Jurassic Penninic ocean, located some distance to the S.

Regarding the depth of the Moho discontinuity along the transect, the map of Posgay et al. (1991) shows this surface in an elevated position at 26 km beneath the Mihályi high. In the central part of the crustal seismic section (Encl. 1) very low frequency reflectors between 9-10 s TWT may correspond to the Moho. Below the Eastern Alps the depth of the Moho descends to 35 km and more (Meissner et al., 1987).

In the southeastern part of the Danube Basin, the pre-Tertiary basement displays a general monoclinal dip to the NW (Fig. 2). Here the Eoalpine structures are reasonably well-known near the top of the pre-Senonian basement, based on the interpretation of the industry seismic profiles (Tari, 1995a). There are a number of NW-verging nappe structures (Fig. 4) that display an Eoalpine deformational style similar to that of the Upper Austroalpine nappes of the Eastern Alps.

The Bakony Mts. consist of the Devecser and Halimba synclines which are superimposed on a much larger synclinal feature trending to the NE. These synclines appear to float above two regional thrust surfaces which can be correlated from outcrops in the Balaton Highland to their subcrop in the Danube Basin (Tari, 1994). Whereas the structurally higher Veszprém thrust is associated with a Carnian detachment level, the deeper Litér thrust generally follows a Middle Triassic detachment level. As these thrusts do not have a clear seismic expression at depth, the interpretation given in Encl. 3 must be considered as conceptual.

To constrain the deep structure of the transect across the Bakony Mts., another crustal line was projected into the regional structure section from some 60 km to the NE (Tari , 1994). The overall synclinal geometry of the Bakony Mts. might be caused by two NW-verging deep thrusts, involving the crystalline basement of the Middle and Lower Austroalpine units. Probably these deep thrusts are responsible for the along-strike appearance of Palaeozoic rocks in the the Velence area, as shown in Figs. 2 and 3.

In the transect, the correlative anticlinal structure under Lake Balaton is distorted because of early Miocene activity along the Balaton "Line". Unfortunately this fault does not have a clear seismic expression. Its reverse fault character at shallow depth was documented by drilling (e.g. Balla et al., 1987; Körössy, 1990). In the transect, the Balaton fault was placed immediately to the N of the Karád wells which bottomed in Dinaric-type Palaeozoic carbonates (Bérczi-Makk, 1988). It is postulated here that the Balaton fault flattens at depth into the base of the Austroalpine nappe system. As an indirect argument for the flattening of the Balaton Line at lower crustal levels an analogy with the the Insubric Line of the Alps is invoked. Heitzmann (1987) and Schmid et al. (1987) demonstrated that the Insubric Line flattens northward at a mid-crustal level and appears to be the westernmost extension of the Periadriatic-Balaton Line system.

Summing up, the most striking result of our transect is that the European foreland crust dips gently (5-10°) beneath the Eastern Alps and extends over a distance of at least 150 and possibly as much as 200 km into the area of the Danube Basin. This supports the earlier held view of Wessely (1987). Although this finding is in keeping with the Central Alpine transect (see Ziegler et al., this volume), it is at odds with the results of a deep crustal profile across the northern Carpathians (Tomek and Hall, 1993) which images an abrupt steepening of the European foreland crust to 70-80° beneath the external Carpathians in Slovakia, about 150 km to the East of the Vienna Basin (see Fig. 1).

DISCUSSION

It appears that during the last decade the role of middle Miocene syn-rift strike-slip faulting in the opening of the Pannonian Basin was overemphasized (e.g. Tari, 1988). Further confusion arose from the fact that throughout the Pannonian Basin numerous flower structures were observed within its post-rift sequence. These structures, however, are related to very recent, and in some cases even currently active fault zones; therefore they cannot be easily assigned to the middle Miocene syn-rift stage of the Pannonian Basin. Instead, they suggest later transpressional deformation of this basin, resulting in the development of local inversion structures (Tari, 1994).

The same holds true for the NW Pannonian Basin as well: seismic evidence clearly shows that low-angle normal faults play an eminent role in the distribution of the different Eoalpine units in subcrop of the Neogene Danube Basin (Fig. 4). Although some oblique-slip movements may have occurred along these detachment fault planes, it must be emphasized that these features are **dominantly** extensional.

The alternate structural model which is proposed here invokes dominantly low-angle normal faulting and opposes the earlier model of dominant strike-slip movement along subvertical faults (e.g. Balla, 1994). The extensional model was tested along the structural transect given in Encl. 3 by gravity modeling (Szafián and Tari, 1995). Preliminary results show that the model based on middle Miocene extensional detachment faulting is indeed viable as a good match was found between the observed and calculated gravity anomalies.

Earlier I addressed the problem of the widely held **assumption** that Cretaceous overthrust planes were reactivated during the Miocene as low-angle normal faults in the Pannonian Basin (e.g. Grow et al., 1989; Tari et al., 1992; Horváth, 1993). Based on the seismic illustrations given in this paper (see also Tari and Horváth, 1995; Tari, 1995a) it is now clear that Neoalpine low-angle normal faults did indeed interact with abandoned Eoalpine thrust fault planes. Such interaction, however, seems to have been more complex than had been anticipated.

The following three ways of interaction between extensional faults and pre-existing thrust faults can be visualized (Fig. 6):

(1) an earlier thrust plane is extensionally reactivated over its entire length (e.g. Ratcliffe et al., 1986),
(2) a newly formed, relatively steeply dipping normal fault soles out at depth into an originally compressional, tensionally reactivated detachment level (e.g. Bally et al., 1966) and
(3) newly formed, extremely low-angle normal faults cut through pre-existing thrust faults and ramp-anticlines (e.g. Wernicke et al., 1985).

Ivins et al. (1990) reviewed the factors, such as geometry, intact/pre-existing fault strength and fluid pressures, which determine whether extensional reactivation will or will not occur, although they did not specifically study the above described geometries.

In the NW Pannonian Basin, reactivation of Cretaceous thrust planes by middle Miocene low-angle normal faults occurred dominantly in the second manner and less typically in the first manner. The geometry where shallow thrusts are cut by

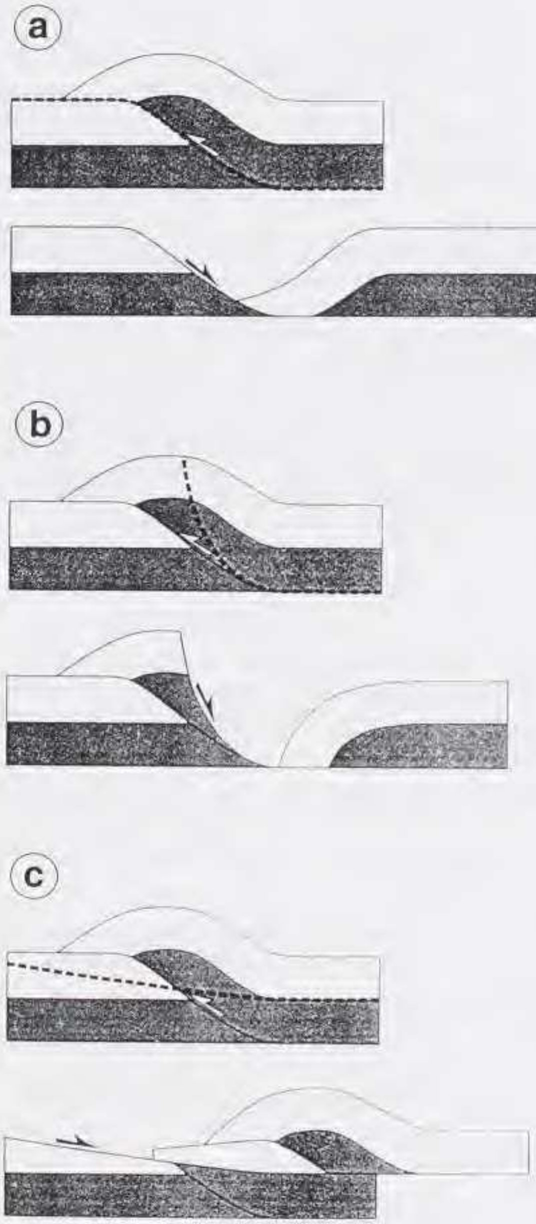

FIG. 6. Different modes of reactivation of pre-existing thrust faults during low-angle normal faulting. In the NW Pannonian Basin mode "b" is the predominant, whereas locally mode "a" can also be observed.

extremely low-angle normal faults was not observed.

The conclusion is that even though reactivation occasionally occurred, Cretaceous overthrust and Miocene extensional detachment fault planes rarely coincide at the top of the pre-Neogene basement or at shallow depth (i.e. <1 km) beneath it. That is why in map view the Répce and Rába faults appear to "ignore" the Austroalpine nappe contacts (Fig. 4). Towards deeper intra-basement levels, however, pre-existing thrust and subsequent low-angle normal faults frequently merge into each other (see also seismic illustrations by Tari, 1995a; Tari and Horváth, 1995).

CONCLUSIONS

The apparent lack of any syn-rift strike-slip structures and the presence of several major low-angle normal faults in the NW Pannonian Basin suggest a primarily extensional origin for the entire Danube Basin as opposed to the traditionally held pull-apart basin interpretation.

Based on the evaluation of reflection-seismic data, the European foreland crust dips at an angle of 5-10° beneath the Alpine/Pannonian junction and extends at least 150 km and possibly as much as 200 km from the Alpine deformation front under the Danube Basin.

The compressionally pre-conditioned "memory" of the basement of the Neogene NW Pannonian Basin influenced the geometry of the subsequent continental extension; partial reactivation of pre-existing regional compressional décollement levels guided the geometry of the newly forming extensional faults.

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Enclosures

Encl. 1. MK-1 crustal reflection profile from Posgay et al. (1986) and its recent reinterpretation by Tari (1994). For location see Fig. 4. See also Encl.3 for the depth-converted geologic section along this seismic profile.

Encl. 2. Line drawing interpretations of the C1, C3, C5 and M18 reflection-seismic sections, adapted from Tari (1994). For location see Fig. 4.

Encl. 3. Regional structure transect across the NW Pannonian Basin by Tari (1994). For location see Figs. 1 to 4. The Austrian part of the transect is based on a geologic section published by Wessely (1988). The middle part of this section is based largely on the deep reflection-seismic profile shown in Encl. 1.